

MODIS Snow and Sea Ice Products

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Popular Summary

In this chapter, we describe the suite of Earth Observing System (EOS) Moderate-Resolution Imaging Spectroradiometer (MODIS) Terra and Aqua snow and sea ice products. Global, daily products, developed at Goddard Space Flight Center, are archived and distributed through the National Snow and Ice Data Center at various resolutions and on different grids useful for different communities. Snow products include binary snow cover, snow albedo, and in the near future, fraction of snow in a 500-m pixel. Sea ice products include ice extent determined with two different algorithms, and sea ice surface temperature. The algorithms used to develop these products are described. Both the snow and sea ice products, available since February 24, 2000, are useful for modelers. Validation of the products is also discussed.

Significance

It is important to describe, in detail, the EOS MODIS snow and ice algorithms and products. Users need this information in order to use the products. Users include university students and researchers and modelers. Many such users do not want to develop their own products from the original MODIS data, a Herculean task, but prefer to use products that have already been developed.

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1.0 Introduction

The Earth's snow and sea ice cover are among the Earth's most dynamic features. Over 40% of the Earth's land surface may be covered by snow cover during the Northern Hemisphere winter, and sea ice covers 5-8% of the ocean surface at any given time. Both snow and sea ice cover act as an effective insulating layer between the atmosphere and land or ocean surface because the low thermal conductivity of snow and sea ice restricts exchanges of heat and chemical constituents between the atmosphere and the land or ocean.

The geographical extent of snow cover over the Northern Hemisphere varies from a maximum of $\sim 46 \times 10^6 \text{ km}^2$ in January and February, to a minimum of $\sim 4 \times 10^6 \text{ km}^2$ in August; between 60 – 65% of winter snow cover is found over Eurasia, and most mid-summer snow cover is in Greenland (Frei and Robinson, 1999). Seasonal snow cover in the Southern Hemisphere is generally located in relatively high mountain areas, such as in the western South America Andes. Sea ice extent varies from a maximum of roughly $15 \times 10^6 \text{ km}^2$ in March, to a minimum of $8 \times 10^6 \text{ km}^2$ in September in the Northern Hemisphere, and a maximum of $20 \times 10^6 \text{ km}^2$ in September to a minimum of $4 \times 10^6 \text{ km}^2$ in February in the Southern Hemisphere (Parkinson et al. 1987).

Numerous studies have shown the importance of accurate measurements of snow and ice extent and albedo, and snow depth and water equivalent, and sea ice concentration and thickness, as they relate to the Earth's climate and climate change (for example, see Dewey and Heim 1981; Barry 1983 and 1990; Ledley et al. 1999; Serreze et al. 2000). Measurements of snow and ice parameters have become increasingly sophisticated over time, and in addition, as the length of the satellite record increases, there is more potential to determine temporal

trends that have climatic significance, that is, if the disparate data sets that comprise the record are well characterized and validated.

Satellites are well suited to the measurement of snow cover and sea ice because the high albedo of snow and sea ice presents a good contrast with most other natural features except clouds. Weekly snow mapping of the Northern Hemisphere using National Oceanographic and Atmospheric Administration (NOAA) National Environmental Satellite, Data, and Information Service (NESDIS) data began in 1966 and continues today in the United States, with improved spatial resolution and on a daily basis (Matson et al. 1986; Ramsay 1998). The NOAA snow-cover record is the longest satellite snow-cover record in history, and it has been studied intensively by Frei and Robinson (1999) and Robinson (1999) so that it is now a consistent record of snow-cover extent from 1966 to present. NOAA's National Operational Hydrologic Remote Sensing Center (NOHRSC) also provides a near-daily (during the snow season), 1-km resolution snow map of the United States and parts of southern Canada (Carroll 1995). Sea ice maps derived from visible, near-infrared and infrared sensors have also been available from the National Oceanic and Atmospheric Administration (NOAA) National Ice Center (NIC) since 1972 (Dedrick et al. 2001), and microwave-derived maps have been available since 1975 (Carsey 1992).

The MODIS snow and sea ice products (<http://modis-snow-ice.gsfc.nasa.gov>), available globally, are provided at a variety of different resolutions and projections to serve different user groups (Hall et al. 2002a and 2004a). The snow maps are available at 500-m and 0.05° resolution on a sinusoidal projection and a latitude/longitude grid known as the climate-modeling grid (CMG). The sea ice maps are available at 1-km and 0.05° resolution, both on the Equal-Area Scaleable Earth grid (EASE-Grid) (see Armstrong and Brodzik, 1995 for information about EASE-Grid).

The snow and sea ice products are archived and distributed through the National Snow and Ice Data Center (NSIDC), one of eight NASA Distributed Active Archive Centers (DAACs), and part of the Earth Observation System Data and Information System (EOSDIS). The products may be obtained through the EOS Data Gateway (EDG) at no charge. The EOSDIS utilizes the EOSDIS Core System (ECS) for data management across the DAACs, and the EDG, which facilitates online Web-based user access to data (Scharfen et al. 2000). Users can search and order data at NSIDC via the EDG client (<http://nsidc.org/imswelcome>).

Throughout the development and production of the snow and ice products, users have been consulted on the suitability of the products. Additionally, users sometimes discover problems in the data products that the developers missed, and alert the developers, making users an integral part of the ongoing QA process. At this writing, Collection 4 (or Version 4) reprocessing of the Aqua land

data product suite (which includes the snow and ice products) has just been completed. Another reprocessing, Collection 5, for Terra and Aqua, will begin about mid 2005. These reprocessings are essential to the integrity of the long-term datasets. There are issues in any long-term dataset that need to be resolved to maximize the accuracy of the data sets, and to produce a viable and accurate segment of a climate-data record. Thus reprocessing is an ongoing process.

There are several different data-product levels starting with Level 2 (L2). An L2 product is a geophysical product that remains in its original image swath format, with the latitude and longitude known precisely; it has not been temporally or spatially manipulated. A Level-2G (L2G) product has been gridded onto a global sinusoidal map projection as a series of 10° latitude by 10° longitude adjoining "tiles," each tile being a piece, e.g., area, of a map projection. (Unlike the original MODIS integerized sinusoidal projection, the sinusoidal projection is well-supported by off-the-shelf geographic-information system and image-processing packages.) Level-2 data products are gridded into L2G tiles by mapping the L2 pixels into cells of a tile in the map projection grid. The L2G algorithm creates a gridded product necessary for development of the Level-3 (L3) products. An L3 product is a geophysical product that has been temporally and/or spatially manipulated.

MODIS algorithms have been developed using the MODIS bands listed in Table 1 to map snow and sea ice and to calculate snow albedo and sea ice surface temperature. These algorithms were modified from heritage algorithms that were successfully used on earlier sensors and are described in detail in the MODIS Snow and Sea Ice User Guides (Riggs et al. 2003a and b). In this chapter, we will describe the MODIS snow and ice products that are available for ordering in 2004 and will be orderable in early 2005. We will also describe validation efforts associated with the products and discuss error analysis.

Table 1. MODIS bands used to produce the MODIS snow and ice products.

Band number	Bandwidth (μm)	Used in Snow and/or Sea Ice algorithms and Terra and/or Aqua	
1	0.62-0.67	Snow & Sea Ice/Terra & Aqua	
2	0.841-0.876	Snow & Sea Ice /Terra & Aqua	
4	0.545-0.565	Snow & Sea Ice /Terra & Aqua	
6	1.628-1.672	Snow & Sea Ice /Terra	
7	2.105-2.155	Snow & Sea Ice /Aqua	

31	10.780-11.280	Snow & Sea Ice/Terra & Aqua	
32	11.770-12.270	Snow & Sea Ice/Terra & Aqua	

2.0 Snow Products

2.1 Introduction

The MODIS snow maps (Table 2) provide global, daily coverage. Swath and daily products are available at 500-m resolution, while the CMG products are provided at 0.05° resolution (~5.6-km resolution at the Equator). Fractional-snow cover or percent snow cover is already available in the CMG products, and in the future, it will be provided in the 500-m products. Because cloudcover often precludes the acquisition of snow cover from visible and near-infrared sensors, 8-day composite products that minimize cloud obscuration complement the daily products. Quality-assessment (QA) information is included in the products.

Table 2. MODIS snow data products.

Long Name	Earth Science Data Type (ESDT)	Spatial Resolution
MODIS/Terra Snow Cover 5-Min L2 Swath 500m*	MOD10_L2	500-m resolution, swath of MODIS data
MODIS/Terra Snow Cover Daily L3 Global 500m SIN Grid (includes daily snow albedo)	MOD10A1	500-m resolution, projected, gridded tile data
MODIS/Terra Snow Cover 8-Day L3 Global 500m SIN Grid	MOD10A2	500-m resolution, projected, gridded tile data
MODIS/Terra Snow Cover Daily L3 Global 0.05Deg CMG	MOD10C1	0.05° resolution, lat/lon climate modeling grid
MODIS/Terra Snow Cover 8-Day L3 Global 0.05Deg CMG	MOD10C2	0.05° resolution, lat/lon climate modeling grid
MODIS/Terra Snow Cover Monthly L3 Global 0.05Deg CMG**	MOD10CM	0.05° resolution, lat/lon climate modeling grid
MODIS/Aqua Snow Cover 5-Min L2 Swath 500m*	MYD10_L2	500-m resolution, swath of MODIS data
MODIS/Aqua Snow Cover Daily L3 Global 500m SIN Grid (includes daily snow albedo)	MYD10A1	500-m resolution, projected, gridded tile data
MODIS/Aqua Snow Cover 8-Day L3 Global 500m SIN Grid	MYD10A2	500-m resolution, projected, gridded tile data
MODIS/Aqua Snow Cover Daily L3 Global 0.05Deg CMG	MYD10C1	0.05° resolution, lat/lon climate modeling grid
MODIS/Aqua Snow Cover 8-Day L3 Global 0.05Deg CMG	MYD10C2	0.05° resolution, lat/lon climate modeling grid

MODIS/Aqua Snow Cover Monthly L3 Global 0.05Deg CMG **	MYD10CM	0.05° resolution, lat/lon climate modeling grid

*A FSC enhancement at 500-m resolution will be available in 2004.

**Future enhancement (see text for explanation).

2.2 MODIS snow-mapping approaches

There are several heritage products that preceded the MODIS snow products. Weekly snow mapping of the Northern Hemisphere NOAA data began in 1966 (Matson et al. 1986) and continues today in the United States, but with improved resolution and on a daily basis (Ramsay 1998). On a more regional scale, Landsat Multispectral Scanner (MSS) (Rango and Martinec 1979), Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+) data have been used for mapping snow-covered area in drainage basins, though no community-endorsed "products" exist. The Landsat TM and ETM+ have been especially useful for measuring snow cover because of the short-wave infrared band – TM or ETM+ band 6 (1.6 μm) – which allows snow/cloud discrimination. The reflectance of snow is low and the reflectance of most clouds remains high in that part of the spectrum. Various techniques, ranging from visual interpretation, multispectral image classification, decision trees, change detection and ratios (Kyle et al. 1978; Bunting and d'Entremont 1982; Crane and Anderson 1984; Dozier 1989) have been used to map snow cover, and many of these techniques are used in the current MODIS snow-mapping algorithm along with additional spectral and threshold tests specific to the MODIS algorithm.

MODIS snow products include the 500-m resolution swath product, (L2G not archived for ordering), the Level 3 500-m resolution product on the sinusoidal grid, the 0.05°-resolution climate-modeling grid products (daily and 8-day composite) and in the future the monthly product derived from the daily CMGs.

The automated MODIS snow-mapping algorithm (Hall et al. 1995 and 2002a) uses at-satellite reflectances in MODIS bands 4 (0.545-0.565 μm) and 6 (1.628-1.652 μm) to calculate the normalized difference snow index (NDSI) based on the heritage algorithms discussed in the previous paragraph:

$$\text{NDSI} = \frac{\text{band 4} - \text{band 6}}{\text{band 4} + \text{band 6}} \quad [1]$$

A pixel in a non-densely-forested region will be mapped as snow if the NDSI is ≥ 0.4 and reflectance in MODIS band 2 (0.841-0.876 μm) and MODIS band 4 (0.545-0.565 μm) are $\geq 10\%$. However, if the MODIS band 4 or band 2 reflectance is $< 10\%$, then the pixel will not be mapped as snow even if the other criteria are met. This threshold test prevents pixels containing very dark targets such as black spruce forests, or clear water bodies from being mapped as snow because very low reflectances cause the denominator in the NDSI to be quite

small, and only small increases in the visible wavelengths are required to make the NDSI value high enough to classify a pixel, erroneously, as snow.

Changes that occur in the spectra of a forest stand as it becomes snow covered can be exploited to map snow cover in forests (Klein et al. 1998). The primary change in reflectance occurs in the visible wavelengths as snow has a much higher visible reflectance than soil, leaves or bark. A fundamental change that snow cover causes in the spectral response of a forest, which can be used in a global algorithm, is that the reflectance in the visible will often increase with respect to the near-infrared reflectance. This behavior is captured in the normalized-difference vegetation index (NDVI), as the presence of snow cover will tend to lower the NDVI. The NDVI (calculated using MODIS bands 1 and 2) and NDSI are used together to improve snow mapping in dense forests. If the NDVI and NDSI values of a pixel lie in a triangular polygon region of NDVI to NDSI space then the pixel may be mapped as snow even if the NDSI is <0.4 (Klein et al. 1998).

The introduction of a "thermal mask" has improved the algorithm by eliminating much of the spurious snow cover that was found in many parts of the globe in the earlier MODIS snow maps. Some causes of the spurious snow cover are confusion with cloudcover, aerosol effects, geologic surface features and snow/sand confusion on coastlines. The thermal mask has greatly reduced errors of commission. Using MODIS infrared bands 31 and 32, a split-window technique (Key et al. 1997), is used to estimate ground temperature. If the temperature of a pixel is $>283\text{K}$, then the pixel will not be mapped as snow (see also Romanov et al. (2000) wherein a thermal mask is described). In cold regions, measured snow-covered area did not change much with the introduction of the thermal mask, but misclassification in warm areas decreased dramatically.

An Aqua-specific version of the L2 snow algorithm was developed in response to MODIS instrument performance issues (see Riggs et al. 2003a). Seventy percent of the Aqua MODIS band 6 detectors are non-functional. The Aqua-specific version of the snow-mapping algorithm uses MODIS band 7 instead of band 6 for the calculation of NDSI. Snow reflectance is similar in both bands 6 and 7 so the difference in snow reflectance in the near infrared relative to the visible is very similar and the NDSI criterion can be applied using band 7 in the ratio.

Aqua-specific settings for the snow criteria tests were determined by using the standard MODIS snow map to determine the NDSI values using band 7 data for pixels that were identified as snow. The NDSI was recalculated using band 7 for the snow pixels and the difference in NDSI values using band 6 or band 7 was determined. Based on analysis of twelve swaths, from different regions in the Northern Hemisphere, it was found that snow at-satellite reflectance is typically a few percent lower in band 7 compared to band 6 in MODIS data. The average difference in NDSI using band 7 was 0.14 lower than when using band 6. Thus,

the NDSI threshold was increased from 0.40 to 0.54 (using band 7), and the NDSI verticies values of the NDSI/NDVI polygon, developed to improve snow cover mapping in forests by Klein et al. (1998), were adjusted by that difference, to produce a snow map from the Aqua MODIS that is very similar to that produced by the Terra MODIS. That approach was taken to maximize compatibility of the L2 snow maps generated with Terra or Aqua data.

Analysis of the Aqua-specific snow map algorithm along with the cloud mask, reveals that in some situations along the periphery of some clouds, the cloud is not detected. In those situations the snow algorithm assumes there is no cloud but the cloud present causes erroneous snow detection by the NDSI/NDVI snow test. As of this writing it appears that the change to band 7 from band 6 has resulted in subtle changes in the ability to detect clouds and snow in such situations (Riggs and Hall in press a). The investigation will continue in order to determine all the effects of the switch to band 7. The NDSI/NDVI test for snow was disabled for the Aqua Collection 4 reprocessing so as to decrease the occurrence of erroneous snow mapping in the Aqua L2 snow products.

2.3 Snow swath product

The snow data-product sequence begins with a 5-minute swath segment (granule) (MOD10_L2 and MYD10_L2) (Figure 1) at a spatial resolution of 500 m and covering 2330 km (cross track) by 2030 km (along track). Coarse resolution, 5km, latitude and longitude data are stored as separate data layers in the product to provide geographic reference. Inputs to the swath snow-cover product are: the MODIS (Level 1B) radiance data (Guenther et al. 1998), the MODIS cloud mask (Ackerman et al. 1998 and Platnick et al. 2003), and the MODIS geolocation product for the latitude and longitude, viewing geometry data and the land/water mask (Wolfe et al. 1998). Only pixels that are on land or inland water and unobstructed by clouds (according to the MODIS cloud-mask product) and in daylight are analyzed for the presence or absence of snow. The product provides a thematic map of snow, cloud (from the MODIS cloud mask) and water (from the land/water mask).

2.3.1 Daily snow fraction

Fractional snow cover (FSC) algorithms and maps have been developed utilizing Landsat, Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) and MODIS data to exploit sub-pixel information. Much of this work has relied on spectral-mixture modeling (see Nolin et al. 1993; Rosenthal and Dozier 1996; Vikhamer and Solberg 2002 and Painter et al. 2003; Dozier and Painter, 2004), and neural networks (McIntire and Simpson 2002) but does not provide global coverage.

Other work using MODIS data (Barton et al. 2001; Kaufman et al. 2002 and Salomonson and Appel, 2004) has been done to develop algorithms to map FSC globally. Using the algorithm developed by Salomonson and Appel, FSC will be

provided in the MOD10_L2 swath snow maps at 500-m resolution (see for example, Figure 2). (An Aqua-specific FSC algorithm is under development.) The FSC enhancement to MOD10_L2 will be available to order in 2005. To develop the FSC algorithm, a statistical-linear relationship was developed between the NDSI from MODIS and the true fraction of snow cover as determined from Landsat scenes from Alaska, Canada and Russia. The fraction of snow cover within a MODIS 500-m resolution pixel can be provided with a mean absolute error of less than 0.1 over the range of 0.0 to 1.0 in fractional snow cover (Salomonson and Appel, 2004). Déry et al. (in press) used the algorithm to infer snow-cover areal depletion curves for the Kuparuk River Basin, and then applied the results in NASA's Catchment-Based Land-Surface Model. Overall, the algorithm appears to do a good job over a wide range of conditions while maintaining relative computational simplicity.

2.4 Daily and 8-day composite gridded snow (tile products)

The second product in the sequence is created by mapping pixels from the swath product to their locations in a MODIS-specific global sinusoidal projection (Wolfe et al. 1998 and 2002) (an integerized sinusoidal projection was used for Versions 1-3 of the data products and a sinusoidal grid is used for Version 4). The Earth is divided into tiles of approximately $10^{\circ} \times 10^{\circ}$ (latitude/longitude) and daily snow products are created for each tile. The daily L2G Terra and Aqua data products (MODL2G and MYD10 L2G, respectively) are intermediate products in which all the observations (pixels) in the snow swath product are geolocated onto the projection, resulting in a three-dimensional data array in which the observations are "stacked."

The 500-m resolution daily Terra and Aqua snow products (MOD10A1 and MYD10A1, respectively) are generated by selecting the observation with the highest score calculated from an observation's solar elevation, distance from nadir and extent of coverage in the grid cell from all the observations acquired during a day. An 8-day composite maximum snow-cover product is produced for each tile by compositing 8 days of the daily tile products. If snow were present on any day in any location on the daily tile product, it will be classified as snow covered in the 8-day composite. Eight-day periods are fixed and begin from the first day of each year. The 8-day periods may go into the following year, but in each new year the 8-day period starts over again on January 1st.

2.4.1 Daily snow albedo

An algorithm has been developed to map snow albedo using MODIS data and is available in the MOD10A1 and MYD10A1 daily tile products. In deriving albedo, atmospherically-corrected MODIS surface reflectances in individual MODIS bands for snow-covered pixels located in non-forested areas are adjusted for anisotropic scattering effects using a DIScrete Ordinates Radiative Transfer model (DISORT) and snow optical properties (Klein et al. 2000; Klein and

Stroeve 2002). Currently in the algorithm, snow-covered forests are considered to be Lambertian reflectors. The adjusted spectral albedos are then combined into a broadband albedo measurement using a narrow-to-broadband conversion scheme developed specifically for snow by Shunlin Liang (written communication 2003) (Liang 2000). Thus derived, a near-global snow albedo product at 500-m resolution (Figure 3) is available from September 15, 2003 to the present as an enhancement to the daily snow-cover product (MOD10A1). Since the product has not yet been validated, it is considered a "beta" product at this writing.

Preliminary validation activities were carried out in February 2003 in northwestern Iowa by Klein (2003). At this time, the snow cover was quite low thus providing the opportunity to evaluate the accuracy of the snow-albedo retrieval from MODIS for pixels containing a mixture of snow and other surface covers. MODIS-derived albedos were found to be within 10% of those measured *in-situ*.

2.5 Daily and 8-day composite global climate-modeling grid (CMG) products

Daily and 8-day composite climate-modeling grid (CMG) products. The daily (MOD10C1 and MYD10C1) and eight-day composite (MOD10C2 and MYD10C2) global climate-modeling grid (CMG) products are available to download from the National Snow and Ice Data Center (NSIDC) (Figure 4). The daily snow-cover CMG product is generated on a geographic grid, by assembling all MODIS land tiles (approximately 320) of the daily 500 m snow product and binning the 500-m cell observations into the 0.05° CMG cells. The binning technique creates an FSC array based on the number of snow observations in a grid cell, a fractional cloud data array based on the number of cloud observations in each CMG grid cell, a confidence index and a QA field (Riggs et al. 2003a). The percentages of snow and clouds in each cell are based on a count of all input observations, including non-snow and non-cloud observations. The confidence index provides a relative measure of the amount of the land surface in a cell that was viewed under clear-sky conditions. The QA field provides an indication of the quality of the 500-m data within each cell. Interpretation of FSC can be difficult because of the extent of clouds in a cell because the fraction of snow cover mapped in a cell is influenced *not* only by the fraction of snow in the cell, but by the fraction of cloud mapped.

The eight-day composite map shown in Figure 4 is produced from the 8-day tile product, MOD10A2. The product is generated by merging all the MOD10A2 products (tiles) for an eight-day period and binning that 500-m data to 0.05° resolution CMG cells to create a global CMG map of snow cover. Input values are binned into categories of snow, cloud, night, etc. The percentages of snow, and cloud, QA and confidence index are computed, based on the binning results for each cell of the CMG, and written into the data arrays.

Errors of commission, mapping snow where none exists, in the eight-day composite global maps have been found to be very low. For example, errors of commission in Australia on three separate 8-day composite snow maps ranged from 0.02-0.10%.

Antarctica is arbitrarily mapped as always completely snow covered in both the daily and 8-day products. Antarctica is 99% or greater snow covered. During the summer up to 1% of the continent may be snow-free mostly on the Antarctic Peninsula. That amount is less than the global error rate for snow mapping. Mapping Antarctica as always snow-covered was done because the MODIS cloud mask maps clouds over Antarctica most of the time, and therefore there are rarely clear views for snow mapping.

2.6 Monthly snow products

To develop the monthly Terra and Aqua snow-cover CMGs (Figure 5) (MOD10CM and MYD10CM, respectively), the mean-fractional snow is computed for each cell from the daily CMG products for the month. If a daily CMG cell has 70% or more clear (cloud free) observations, the cell will be used in the calculation for the monthly product. An average is taken of the FSC in all the cells in a month that meet that criterion.

The monthly MODIS snow products should be useful for modelers, and for continuation of climatological snow-cover records (see for example, website for Rutgers University Climate Lab <http://climate.rutgers.edu/snowcover/>) and Hall et al. (2004b) and will be available to order through NSIDC in 2004.

2.7 Validation

The MODIS daily snow maps compare well with existing NOAA daily or near-daily snow maps such as the NOAA NESDIS and NOHRSC maps. MODIS has two major advantages over the NESDIS maps. The use of the short-wave infrared bands (MODIS bands 6 and 7 permits improved snow/cloud discrimination), and the 500-m resolution is an improvement compared to the ~25-km resolution of the NESDIS maps. Additionally, MODIS often maps snow more frequently (i.e., more than once per day) than do the NESDIS maps thus providing information on fleeting snow cover that may have only lasted for a few hours (Hall et al. 2002b). Sometimes fleeting snow cover, and snow cover at the edges of snow-covered areas, is not mapped by NESDIS. Relative to the NOHRSC maps, the 500-m resolution of the daily MODIS maps is an improvement over the 1-km resolution of the NOHRSC maps, and MODIS maps snow globally for the entire year, while the NOHRSC maps are provided only of the United States and parts of southern Canada during the snow season. However, the important advantage of the NOAA maps, from a prediction standpoint, is that these maps utilize multiple sources of data to map snow cover including satellite and ground observations. From the standpoint of developing a

climate-data record, this is more problematic than maps derived from an automated algorithm (as in the case of the MODIS products) because even if snow maps derived from automated algorithms are later determined to be incorrect, they can be reprocessed in a uniform manner.

Bitner et al. (2002) compared NESDIS and MODIS snow maps with the NOHRSC map. NOHRSC snow cover maps were compared with MODIS snow-cover maps in the Pacific Northwest and the Great Plains for 18 and 21 days, respectively, between March and June of 2001. The MODIS 500-m resolution product was degraded to match the resolution of the NOHRSC product (1 km). The agreement was reported to be 94% in the study area in the Pacific Northwest and 95% in the study area in the Great Plains. The largest disparity in snow-cover mapping between the NOHRSC and MODIS maps was at the edges of the snowpack where MODIS mapped more snow. (As mentioned previously, the MODIS maps often map more snow at the edges of snow-covered areas because several swaths may be mapped per day; if snow falls and melts within a few hours, MODIS is likely to capture it in the daily product.) However within the perimeter of a snowpack, the NOHRSC maps showed a more continuous snowpack when compared with the MODIS indicating that in mid-winter, the agreement between the products is good.

Klein and Barnett (2003) studied NOHRSC and MODIS snow maps and SNOpack TELelemetry (SNOTEL) in-situ measurements in the Upper Rio Grande Basin for the 2000-2001 snow season, and found that the agreement between snow maps was about 86%, and the MODIS and NOHRSC snow products showed agreements of 94% and 76% with the SNOTEL measurements, respectively. A time-series comparison between MODIS retrievals and SNOTEL over the entire snow season showed an overall classification accuracy for MODIS of 88%, though the errors of commission and omission were found to be 12% and 15%, respectively, with much of the discrepancy occurring early and late in the snow season in thin snowpack conditions.

Mauer et al. (2003) compared MODIS and NOHRSC data for 46 days in the Columbia River Basin, and 32 days in the Missouri River basin during the winter and spring of 2000-2001. The presence or absence of snow was determined from ground observations at meteorological stations. On average, the MODIS snow maps classified fewer pixels as cloud as compared to the NOHRSC maps which permitted 15% more of the Columbia River basin area to be classified as to the presence or absence of snow relative to when NOHRSC maps were used. They found that the maps were comparable, but the MODIS maps generally provided more cloud-free data than did the NOHRSC.

MODIS and NOAA products acquired over Canada were compared with observations from almost 2,000 meteorological stations by Simic et al. (2004). Results showed similar agreement (ranging from ~80%-100% on a monthly basis). Evergreen forests showed the lowest percentage agreement of all land-

cover types studied. This is consistent with results found in Hall et al. (2001). The agreement between the MODIS snow maps and the meteorological-station data was generally found to be lower during the early part of the snow season by Simic et al., and during snow melt, particularly in forested areas (Simic et al. 2004).

Comparisons of MODIS CMG snow-cover maps with SSM/I snow-cover maps show that the MODIS maps are generally superior for mapping areal extent of snow cover especially in the early part of the snow season (Hall et al. 2002b). Earlier, other authors showed that same result using NESDIS and SSM/I snow maps (Basist et al. 1996 and Armstrong and Brodzik 1999). Hall et al. (2002b) show differences up to 5.32 million km² in the amount of snow mapped using MODIS versus SSM/I, with the MODIS data being more accurate. Bussi res et al. (2002) also compared MODIS-derived snow maps with SSM/I-derived snow maps over the prairie and boreal forest region in western Canada, and the taiga region in eastern Canada and found generally good correspondence, however, the SSM/I maps were not as accurate as were the MODIS in the fall and spring. As the snow deepens during the winter, and the temperatures become consistently colder, the ability of the SSM/I to map snow improves, and the agreement between the visible and passive-microwave maps improves. This is because the passive-microwave data are not able to map wet snow cover because the penetration of the microwave signal when the snow is wet is extremely low. But of course the passive-microwave-derived maps have the potential to map snow-water equivalent and snow depth and the MODIS maps do not.

3.0 Sea Ice Products

3.1 Introduction and algorithm description

Daily extent and ice-surface temperature (IST) maps are produced using MODIS data at 1-km resolution (Table 3). Algorithms for deriving the sea ice maps from MODIS are similar for both the Terra and the Aqua MODIS instruments, and are used to generate maps of sea ice extent as determined by reflectance and IST (Riggs et al. 1999 and 2003b). The products are produced globally at both 1-km and 0.05  (or ~4-km at the Equator) spatial resolution. During daylight hours, two sea ice maps are produced; one is derived from surface reflectances and the other from IST while at nighttime, only the IST is produced. MODIS sea ice products are generated automatically using MODIS sensor-radiance data (Guenther et al. 1998 and 2002), a geolocation product (Wolfe et al. 2002), and the MODIS cloud mask product (Ackerman et al. 1998 and Riggs and Hall in press b). In addition to sea ice extent and IST, QA, latitude and longitude, and other information is also included with the data products (Riggs et al. 2003b).

Sea ice extent is computed in two ways: by reflectance and by IST. Sea ice extent is determined by the characteristic of snow-covered sea ice to have high visible reflectance and low reflectance in the short-wave infrared. The sea ice algorithm uses the NDSI (described in Sec. 2.1) and visible reflectance criteria to map sea ice. Sea ice extent by IST is computed using the IST (see section 3.2), but the user can select a temperature cutoff below which the pixel is considered ice and above which it is considered water. The MODIS cloud-mask product is relied on for masking cloudy pixels for analysis of sea ice.

Though the sea ice extent algorithms for Terra and Aqua are very similar, the major difference is that for Terra, MODIS band 6 data are used; for Aqua, MODIS band 7 data are used because of the non-functioning detectors in the Aqua MODIS band 6. Minor differences in mapping sea ice attributable to using band 7 may be observed where the ice signal is weak and confusion between sea ice and clouds may occur in some situations.

Table 3. MODIS sea ice data products.

Long Name	Earth Science Data Type (ESDT)	Spatial Resolution
MODIS/Terra Sea Ice Extent 5-Min L2 Swath 1km	MOD29	1-km resolution, swath of MODIS data
MODIS/Terra Sea Ice Extent Daily L3 Global EASE-Grid Day	MOD29P1D	1-km resolution, projected, gridded tile data
MODIS/Terra Sea Ice Extent Daily L3 Global EASE-Grid Night	MOD29P1N	1-km resolution, projected, gridded tile data
MODIS/Terra Sea Ice Extent and Ice Surface Temperature Daily L3 Global 4km EASE-Grid Day [±]	MOD29E1D	4-km resolution, global, gridded
MODIS/Terra Ice Surface Temperature Daily L3 Global 4km EASE-Grid Night *	MOD29E1N	4-km resolution, global, gridded
MODIS/Terra Sea Ice Extent and Ice Surface Temperature 8-Day L3 Global EASE-Grid Day *	MOD29E2D	4-km resolution, global, gridded
MODIS/Terra Ice Surface Temperature 8-Day L3 Global EASE-Grid Night*	MOD29E2N	4-km resolution, global, gridded
MODIS/Terra Sea Ice Extent and Ice Surface Temperature Monthly L3Global 4km EASE-Grid Day*	MOD29EMD	4-km resolution, global, gridded
MODIS/Terra Ice Surface Temperature Monthly L3Global 4km EASE-Grid Night *	MOD29EMN	4-km resolution, global, gridded
MODIS/Aqua Sea Ice Extent 5-Min L2 Swath 1km	MYD29	1-km resolution, swath of MODIS data
MODIS/Aqua Sea Ice Extent Daily L3 Global EASE-Grid Day*	MYD29P1D	1-km resolution, projected, gridded tile data
MODIS/Aqua Sea Ice Extent Daily L3 Global EASE-Grid Night*	MYD29P1N	1-km resolution, projected, gridded tile data

MODIS/Aqua Sea Ice Extent and Ice Surface Temperature Daily L3 Global 4km EASE-Grid Day*	MYD29E1D	4-km resolution, global, gridded
MODIS/Aqua Ice Surface Temperature Daily L3 Global 4km EASE-Grid Night *	MYD29E1N	4-km resolution, global, gridded
MODIS/Aqua Sea Ice Extent and Ice Surface Temperature 8-Day L3 Global EASE-Grid Day *	MYD29E2D	4-km resolution, global, gridded
MODIS/Aqua Ice Surface Temperature 8-Day L3 Global EASE-Grid Night*	MYD29E2N	4-km resolution, global, gridded
MODIS/Aqua Sea Ice Monthly Global EASE-Grid *	MYD29EMD	4-km resolution, global, gridded

*Future enhancement or product (to be implemented in 2004).

3.2 Calculation of sea ice-surface temperature (IST)

Measurement of IST is possible with sensors having thermal-infrared bands such as the Temperature Humidity Infrared Radiometer (THIR), Advanced Very High Resolution Radiometer (AVHRR), Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+). For the retrieval of clear-sky IST, a split-window technique is typically used when possible, where “split-window” refers to brightness-temperature differences in the 11-12 μm atmospheric window. This technique allows for the correction of atmospheric effects, primarily due to water vapor (Key and Haeffliger 1992; Key et al. 1994 and 1997; Comiso 2001) and MODIS (Hall et al. 2004a).

An identical IST algorithm is used for both the Terra and Aqua MODIS sea ice products (Hall et al. 2004a). For the retrieval of clear-sky IST, a split-window technique is used, where “split-window” refers to brightness temperature differences in the 11-12 μm atmospheric window. This technique allows for the correction of atmospheric effects, primarily water vapor. First employed to determine sea-surface temperature (SST) (Prabhakara et al. 1974), the technique was subsequently used to determine IST in the Arctic with the AVHRR on NOAA polar-orbiting satellites (Key and Haeffliger 1992). For MODIS IST, the split-window technique is implemented as a simple regression model of the form

$$T_s = a + bT_{11} + c(T_{11} - T_{12}) + d[(T_{11} - T_{12})(\sec \theta - 1)] \quad [2]$$

where T_s is the surface temperature, T_{11} and T_{12} are the MODIS-measured brightness temperatures in the 11 and 12 μm channels (MODIS channels 31 and 32), θ is the sensor scan angle, and a , b , c , and d are regression coefficients. The split-window temperature difference is proportional to the atmospheric water

vapor amount, and the scan angle provides information on the atmospheric path length.

To determine the empirical relationship in eq. [2], radiosonde data from drifting ice and land-based stations were used with a radiative-transfer model, LOWTRAN (Kneizys et al. 1988), to simulate the sensor-brightness temperatures. The sensor spectral response functions were convolved with the calculated radiances and converted to brightness temperatures for each radiosonde profile. The surface temperatures used in the model calculations were then regressed against the simulated brightness temperatures to determine the coefficients in eq. [2]. The regression coefficients in eq. [2] were determined separately for the Arctic and Antarctic and for three temperature ranges.

3.3 Swath products

As with the snow-cover products, MODIS sea ice data products are produced as a sequence of products, beginning with a swath (scene) at a nominal pixel spatial resolution of 1 km and a nominal swath coverage of 2330 km (cross track) by 2030 km (along track) (about five minutes of satellite travel) (MOD29 and MYD29) (Table 3). Figure 6 illustrates the MOD29 IST product acquired on March 12, 2003, in the northern Greenland Sea in the Arctic Ocean.

3.4 Daily and 8-day composite gridded sea ice products (tile products)

Automated selection of the most favorable observation from all the swaths acquired during a day generates a daily gridded sea ice product on the EASE-Grid at 1-km spatial resolution (MOD29E1D, MOD29E1N, MYD29E1D and MYD29E1N). This product includes both ice extent and IST. Eight-day composite sea ice products will be available in 2004.

3.5 Global-scale daily, 8-day composite and monthly gridded products

A daily global sea ice product of sea ice extent and IST for the north and south polar areas in the EASE-Grid projection at 0.05° resolution (Figure 7) is available for Terra data (MOD29E1D). The Aqua product (MYD29E1D) will be available in 2004. Daytime and nighttime versions of the daily global sea ice product will eventually be available. In 2005, an 8-day composite global sea ice product, derived from the daily maps, will also be available and will provide the maximum ice extent and average IST during the eight-day period (MOD29E1D, MOD29E1N, MYD29E1D and MYD29E1N).

Monthly sea ice products containing sea ice extent and IST maps (MOD29EMD, MOD29EMN, MYD29EMD and MYD29EMN) will be available in 2005.

3.6 Validation

Validation activities during the “cold period” (when meltwater is generally not present) in the Northern Hemisphere have been undertaken to assess the accuracy of the 1-km resolution MODIS IST algorithm and product (Hall et al. 2004a). Validation was also done at the Amundsen-Scott South Pole station in Antarctica using data from an automatic weather station. In the Arctic Ocean, near-surface air temperatures from the National Oceanic and Atmospheric Administration (NOAA) National Ocean Service (NOS) Center for Oceanographic Operational Products and Services (CO-OPS) Alaska tide stations, and from drifting buoys from the North Pole Environmental Observatory (NPEO) buoy program were compared with MODIS-derived ISTs. Using the standard MODIS sea ice product which utilizes the MODIS cloud mask, ISTs show a bias (mean error) of -2.1K and an RMS error of 3.7K. The negative bias means that the satellite retrieval is less than the air temperature. With the bias removed, the RMS error is 3.0K.

When additional visual cloud screening is performed to eliminate MODIS pixels thought to be contaminated by fog, results improved, with a subset of the larger data set showing a bias of - 0.9K and an RMS error of 1.6K (Figure 8). With the bias removed, the RMS error for the Arctic Ocean observations is 1.3K. At the South Pole, under clear skies as determined using lidar measurements, the MODIS ISTs are also very close to near-surface air temperatures with a bias of - 1.2K and an RMS error of 1.7K. With the bias removed, the RMS error for the South Pole observations is 1.2K. Thus the accuracy (RMS error) of the IST measurement is 1.2-1.3K. However, it is not possible to obtain an accurate IST from MODIS in the presence of even very thin clouds or fog, making this the main limitation of the MODIS IST product.

4 Limitations inherent in the snow and sea ice products

4.3 Land masking in the snow and sea ice data products

A 1-km resolution U.S. Geological Survey (USGS) global land/water mask, stored in the MODIS geolocation product, is used by all the MODIS land algorithms to determine if a pixel is land or ocean for processing (Wolfe et al. 2002). An issue with the land/water mask is that ice shelves, such as the Ross Ice Shelf of Antarctica, are classified as land and not ocean. Consequently, ice shelves have not been included in the MODIS sea ice products (Riggs et al. 2003b). A MODIS derived land/water mask, using several years of MODIS land cover data products has been developed by the MODIS Land Cover Product Team. That land/water mask has greater accuracy for mapping of land cover products. Integrated into that land/water mask were the Antarctic Digital Database grounding lines. That Antarctic map puts the continental land boundary at the grounding lines thus the ice sheets are properly put in the ocean and in the sea ice data products. Initial test results revealed great improvement in the quality of the sea ice products because the ice sheets were included in

them. Additionally the snow products were improved because the ice sheets were removed from them. Evaluation of the MODIS land/water mask for snow mapping relative to inland water bodies is underway at the time of this writing. It is anticipated that all land products in the Collection 5 reprocessing and forward reprocessing will use the MODIS land/water mask. Following its implementation, it will be possible to monitor large icebergs such as those that have recently calved from the Ross Ice Shelf, using the sea ice products.

4.2 Cloud masking

A challenging problem in snow and sea ice detection is the discrimination of snow or sea ice from clouds (Ackerman et al. 1998 and Riggs and Hall in press b). Snow has rather unique spectral characteristics compared to most other terrestrial surface features with a high reflectance in the visible and strong absorption in the infrared spectral regions. Those characteristics are key to detection of snow by use of the NDSI, however some types of clouds exhibit very similar spectral characteristics to snow which can make discrimination between snow and clouds very difficult.

The L-2 snow and sea ice algorithms use the MODIS cloud-mask product. The MODIS cloud-mask algorithm takes a cloud-conservative approach to cloud detection. The cloud algorithm uses fourteen of the 36 MODIS bands in 18 cloud spectral tests that follow different processing paths depending on surface type, geographic location and ancillary data input. Results of all cloud tests and associated processing flags are stored in the cloud-mask data product. The summary result of whether a pixel is cloudy, clear or probably clear is reported in a single summary flag of the cloud algorithm for a pixel. A complete description of the cloud mask algorithm is presented in Ackerman et al. (1998) or at the MODIS Atmospheres website, http://www.modis-atmos.gsfc.nasa.gov/MOD35_L2/index.html. The summary cloud flag is used as the cloud mask within the snow and sea ice algorithms. However, ongoing evaluation of the cloud masking performance as it relates to snow and sea ice detection has exhibited evidence that masking of clouds can be improved by selective use of individual cloud test results stored in the cloud mask product (Riggs and Hall in press b).

Snow or sea ice detection is primarily dependent on the NDSI in the MODIS snow and sea ice algorithms. The NDSI is insensitive to most clouds except for some clouds containing ice and in some situations where the spectral signature of the cloud is similar to that of the snow. The MODIS cloud-masking algorithm contains many spectral tests; of those, we found that three can be used in the snow algorithm to minimize cloud obscuration over snow, and to mask clouds where the clouds completely obscured the surface in the L2 snow products. In MOD10_L2 products in Collection 4 there is an snow extent map using a selected group of cloud-mask tests, called the "liberal" cloud mask, in addition to the snow extent map made using the summary cloud flag. The liberal cloud

mask and its resulting snow-extent map is experimental because there are some situations where clouds over a snow-covered surface are not identified as clouds by the liberal cloud mask. This results in a map that shows a bare surface when in fact the surface is snow covered. This is perhaps worse than showing cloud cover when it does not exist because it appears to a user that no snow is on the ground. Investigation continues into how to make better use of data from the cloud mask and to structure the snow algorithm to correctly identify the features in those situations. Similar lines of investigation are being pursued in the sea ice algorithm in both daytime and nighttime situations.

The accuracy of the MODIS cloud mask over snow and ice varies, with the highest accuracy generally found for daytime data and the lowest accuracy in darkness over sea ice using the thermal-infrared channels. Low illumination and the similar reflectance characteristics of clouds and sea ice at visible wavelengths cause difficulties in cloud masking using MODIS data. Additionally, atmospheric inversions can cause surface temperatures to be colder than the temperature of some clouds (e.g., McIntire and Simpson 2002). Snow or ice/cloud discrimination problems are compounded during the polar night because the MODIS reflective bands are not useful during darkness. The absolute accuracy of the MODIS cloud mask used in the sea ice algorithm is unknown. The Aqua MODIS cloud mask algorithm was revised to use band 7 (2.1 μm) in place of band 6 (1.6 μm) because of the non-functional detectors on the Aqua MODIS in band 6 as described earlier. The revised Aqua cloud-mask algorithm has been in use since May 20, 2003, and has altered the masking of clouds over sea ice relative to the original cloud mask used with the Terra MODIS products.

A particular problem for mapping clouds over sea ice is the identification of thin clouds and fog. Fog often develops in sea ice covered waters when water vapor forms following the formation of leads and polynyas. While it may be possible to see the sea ice on a MODIS image, and even map the sea ice through the fog, it is not possible to retrieve an accurate IST through fog, even with the many visible, near-infrared, short-wave infrared and infrared MODIS bands.

5 Discussion and Conclusion

The algorithms used to develop the MODIS snow and sea ice map products were developed from heritage snow and sea ice algorithms that primarily employed Landsat and AVHRR data as well as aircraft data to map snow. The MODIS products compare favorably with the heritage products and represent improvement in terms of resolution, both spatial and spectral and also in terms of cloud masking. Furthermore, the fully-automated nature of the MODIS algorithms make the resultant products suitable as components of climate-data records. Through the National Snow and Ice Data Center, and the Earth

Observing System Data Gateway one can order the data products and they are provided free-of-charge to the user.

The MODIS products have been reprocessed twice. (Note: the collection/version number are not the same as the processing. The original processing was Version 1 for Terra but there was no Version 2, and then there was a jump to Version 3.) The next reprocessing, also known as "Collection 5," will begin in mid 2005 and will take several months to complete. The reprocessings are necessary in order to include improvements in the algorithms, and to fix problems that are noticed by either the developers or users. The most up-to-date Terra MODIS products are in Collection 4, or Version 4. Aqua Collection 4 reprocessing began in January 2004 and was completed in July 2004.

Collection 4 MODIS snow maps have been validated and compared quantitatively with operational snow maps as well as with field and meteorological measurements. Results show that the MODIS snow maps are providing snow extent generally within $\pm 5\%$ of the actual snow extent, except in forested areas where the errors are sometimes greater and more variable. The cloud mask contributes additional errors. The MODIS snow maps also provide daily snow albedo (as a beta product) and fractional-snow cover from both the 500-m (in Collection 5) and CMG maps. While the 500-m resolution maps are most useful for hydrological modeling, the CMG maps (daily, 8-day composite and average monthly) are useful for global-scale modeling.

The MODIS sea ice maps provide validated sea ice extent and ice-surface temperature at a resolution of 1 km during the daytime. Maps are also provided during the polar night but are not yet validated due to the extreme difficulty in reliably distinguishing clouds and snow/ice during darkness. Global-scale, 0.05°-resolution sea ice extent and IST maps (daily, 8-day composite and monthly) on the EASE-Grid are under development and should be available in 2004.

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Figures

1a. MODIS true color image of the eastern United States acquired on December 7, 2003, showing the first big snowstorm of the season. Courtesy MODIS Rapid Response Team.

1b. MODIS swath-based snow map (MOD10_L2) of the area shown in Figure 1a. Snow is white, snow-free land is green and clouds are pink. Water is shown in blue.

2. Prototype of the 500-m resolution fractional-snow cover product that will be available as part of the snow-cover swath product, MOD10_L2. This map covers parts of the mid-western and western United States and was acquired on December 14, 2000.

3. Examples of the 500-m resolution daily snow albedo product, included in MOD10A1, from two dates in November of 2003.

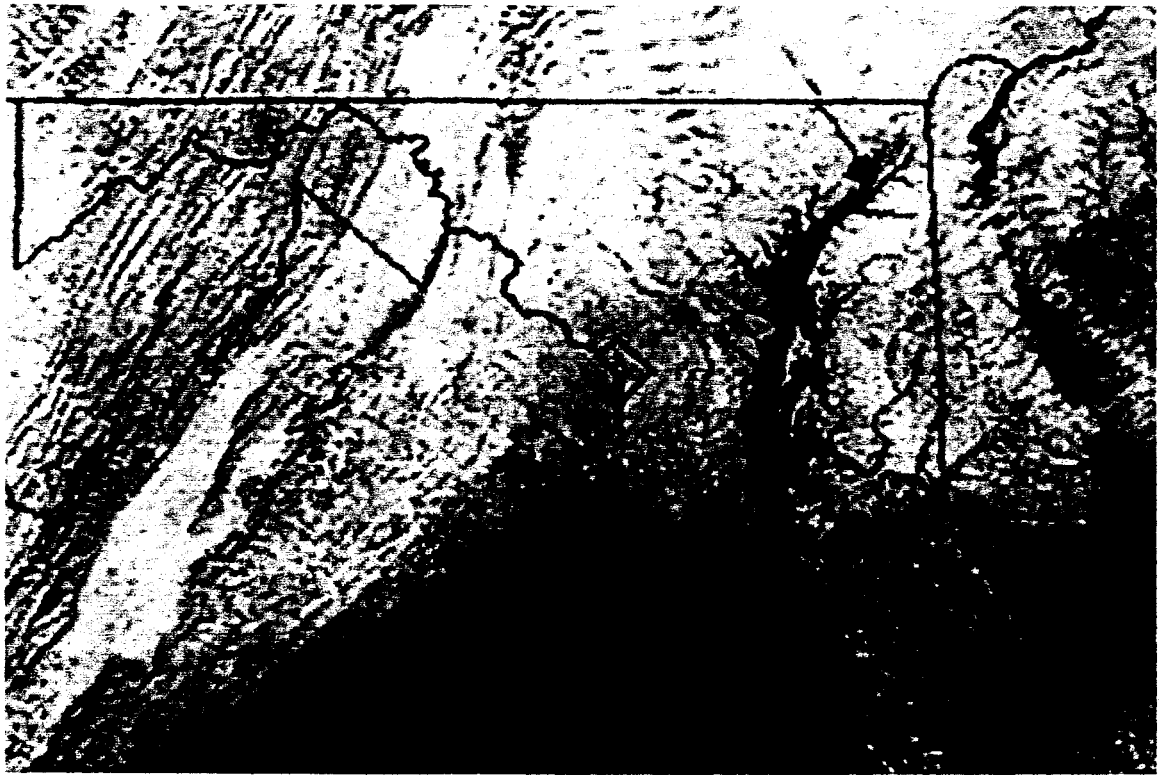
4. Eight-day composite (April 6-13, 2000) climate-modeling grid (CMG) global snow map, MOD10C2.

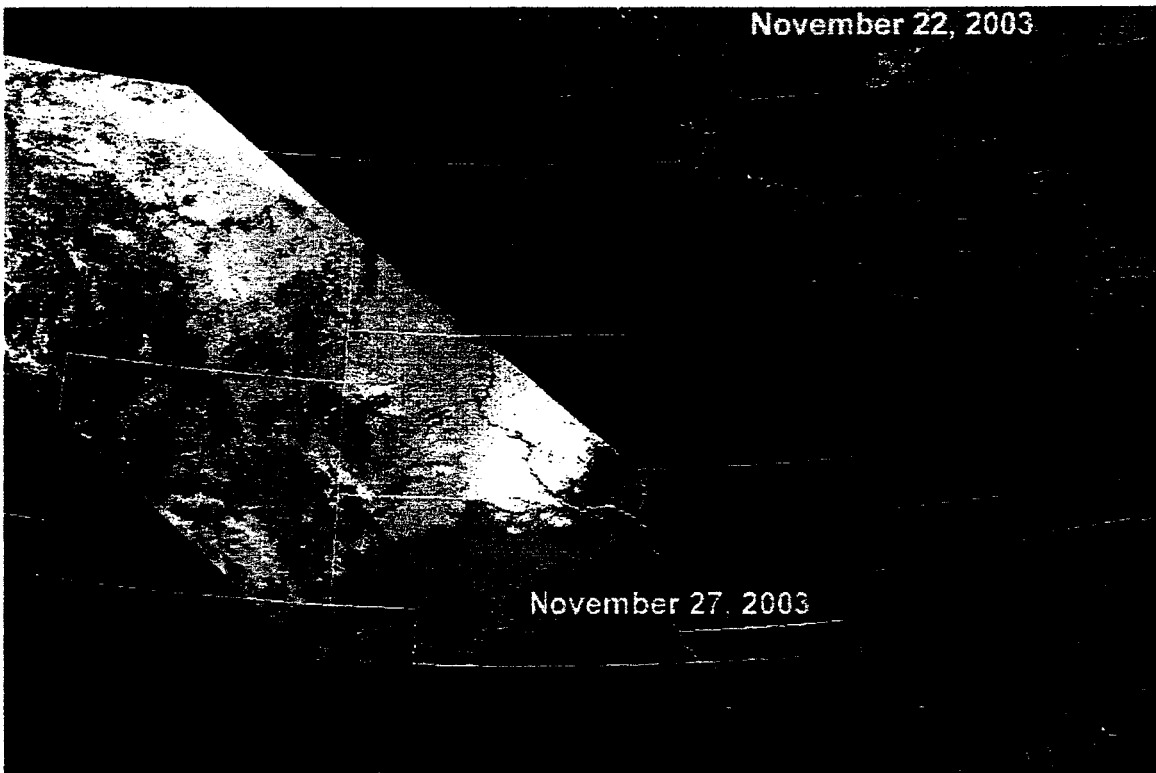
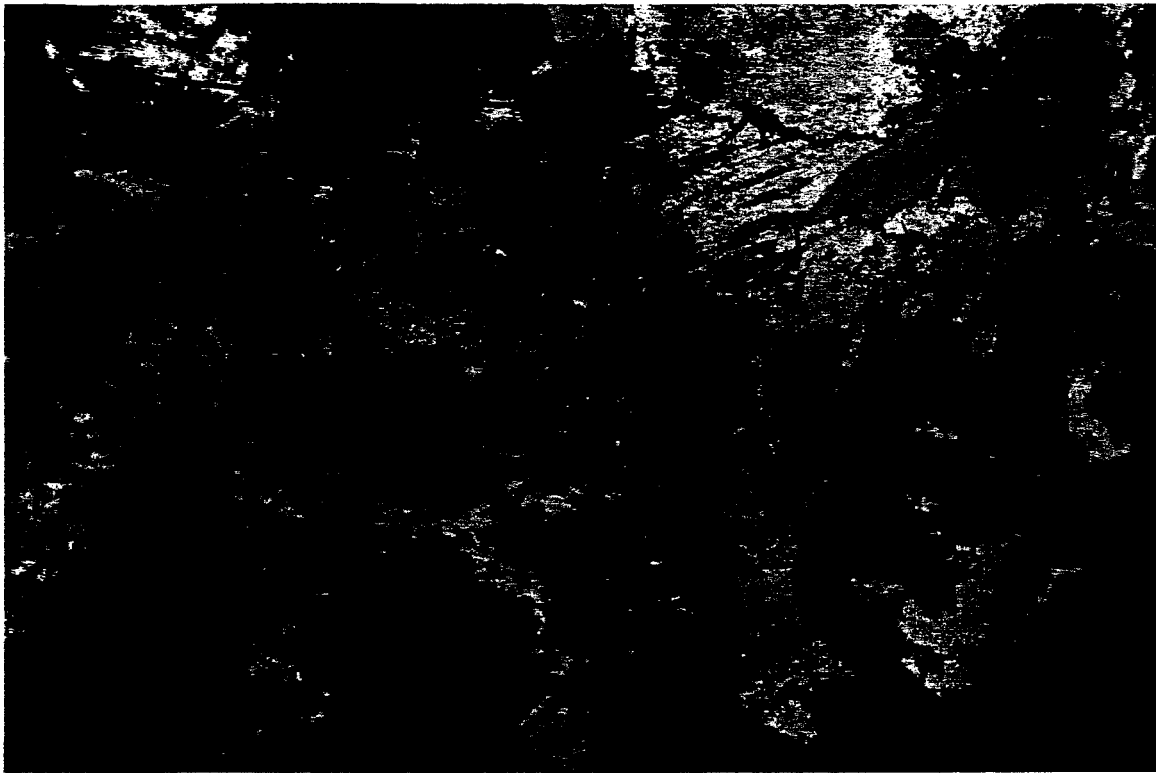
5. Prototype of the monthly snow map on the climate-modeling grid (CMG), MOD10CM.

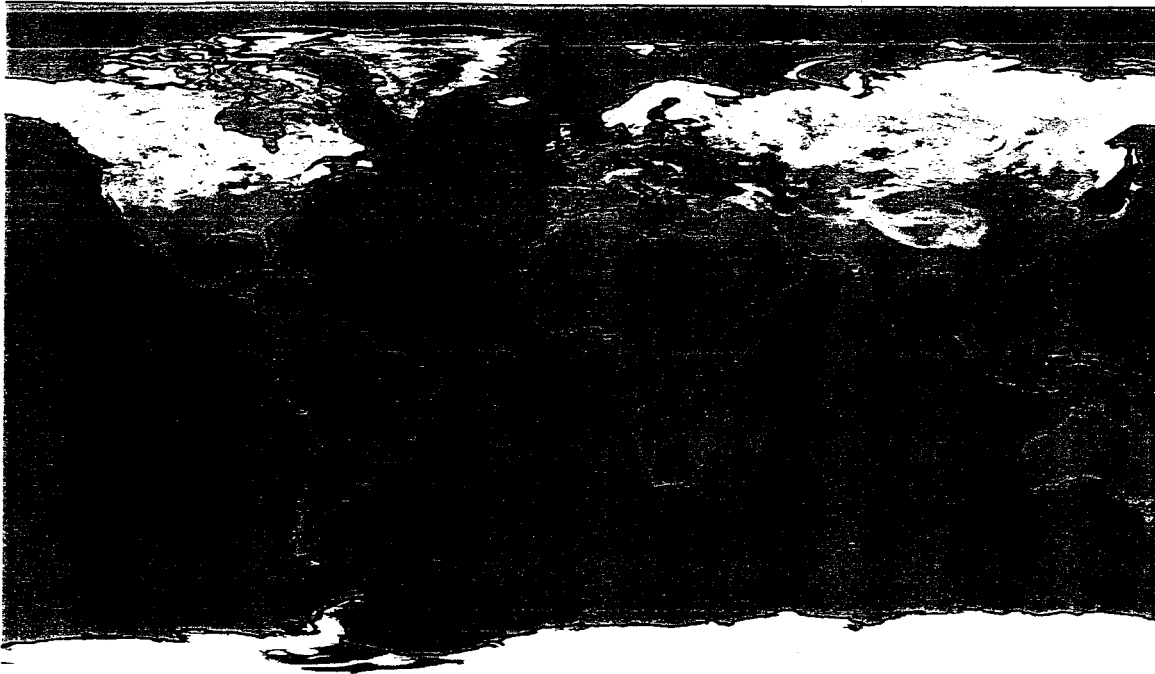
6. Terra MODIS ice-surface temperature (IST) product (MOD29) acquired on March 12, 2003 (18:45 UTC), in the northern Greenland Sea in the Arctic Ocean. The approximate center point of the image is 81.7° N, 1.0° E. The color scale represents IST in K (from Hall et al. 2004a).

7. Prototype (average of May 15-19, 2000) of the future eight-day composite sea ice-surface temperature (IST) global EASE-Grid composite product of the north polar area MOD29C2 (prototype utilizes only five days of data). Color key shows ISTs from 230-271K. The color scale represents IST in °K. Clouds are shown in pink. In the compositing algorithm, each cell must be mapped as sea ice for two consecutive days otherwise it will appear as cloud. This reduces the errors of commission in the composited product (from Hall et al. 2004a).

8. MODIS IST-retrieved skin temperatures and measured surface temperatures in three different areas of the Arctic Ocean on various dates between January 25, 2002, and May 22, 2003. In the comparison, MODIS pixels were visually screened for the likely presence of cloud or fog. The in-situ temperatures were acquired from the Japan Marine Science and Technology Center (JAMSTEC) Compact Arctic Drifter #4 and #5, or J-CAD 4 and J-CAD 5 buoys, and from the tide station at Prudhoe Bay, AK (from Hall et al. 2004a).







☒ water ☒ non- snow ☒ cloud ☒ no decision ☐ sn



☒ 1-19% ☒ 20-39% ☐ 40-59% ☒ 60-79% ☐ 80-100% ☒ no decision

